1.0 INTRODUCTION

1.1 Introduction

This report is a detailed characterization of the ground motions that might affect Jackson Lake Dam due to a large earthquake on the Teton fault. Advances in the understanding of strong ground motions over the past decade have accrued due to the recording of several large earthquakes and research efforts to understand the seismic source, propagation, and site effects that produce and influence recorded ground motions. These efforts have lead to the development of improved methods of estimating and predicting strong ground motions at sites such at Jackson Lake Dam. These new data and approaches highlight the importance of geologic structure, basin geometry and properties, and site response to at-site ground motion estimation. Prior approaches to estimating ground motions at Jackson Lake Dam (USBR, 1987, Wong et al., 2000) relied on either simplified approaches or empirical data approaches that did not extensively incorporate these factors.

The surface trace of the Teton fault lies along the western shore of Jackson Lake, about 12 km (7 mi) west of Jackson Lake Dam (Figure 1-1). Late Quaternary fault scarps, formed by multiple Holocene surface faulting events, are present along about 60 km (37 mi) of the fault trace. The fault dips to the east forming a deep basin of late Cenozoic alluvial fill. Jackson Lake Dam was constructed on the eastern margin of this basin. At the damsite, largely unconsolidated late Quaternary alluvium ranges in thickness from zero on the south abutment to nearly 500 ft under the northern section of the dam. Although there are numerous earthquakes and potential seismic sources in the region, previous engineering analyses of Jackson Lake Dam by Reclamation have assumed that the Teton fault is the controlling seismic source for analyses of the dam based on proximity, activity rates, and maximum earthquake magnitudes. This assumption appears to be confirmed by results from a preliminary probabilistic hazard analyses (Wong et al., 2000). Thus, the primary focus of this study is on developing ground motions for large earthquakes on the Teton fault.

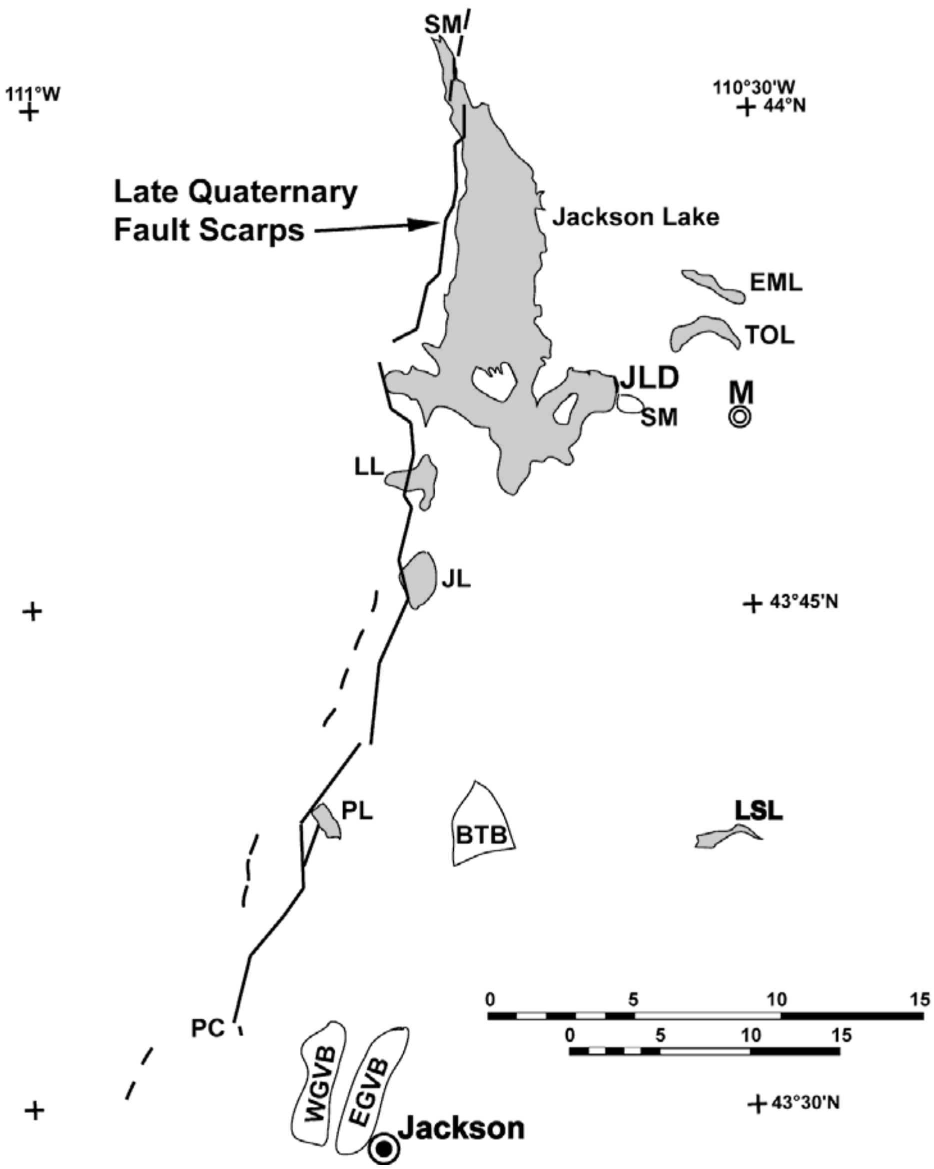

Figure 1-1: Map showing location of Jackson Lake Dam and late Quaternary trace of Teton fault. SM-Steamboat Mountain; EML-Emma Matilda Lake; TOL-Two Ocean Lake; JLD-Jackson Lake Dam; M-Moran; LL-Leigh Lake; JL-Jenny Lake; PL-Phelps Lake; BTB-Blacktail Butte; LSL-Lower Slide Lake; PC-Phillips Canyon; WGVB-West Gros Ventre Butte; EGVB-East Gros Ventre Butte.

1.2 Objectives and Scope

The objective of the Dam Safety investigations at Jackson Lake Dam is to reach a decision addressing whether or not additional modifications to the dam are reasonably required in accordance with the Reclamation Safety of Dams Act. The objective of this report is to provide estimates of the site-specific ground motions that might affect Jackson Lake Dam as a result of a large earthquake on the Teton fault. These ground motion results are intended as inputs for engineering analyses of the stability of the dam during large earthquakes as part of an overall risk assessment for Jackson Lake Dam. Because the foundation of the dam consists of a varied thickness of unconsolidated alluvium and the site is located on the margin of a large structural basin, particular emphasis in the current ground motion analyses is to investigate aspects of seismic wave propagation and site response on estimates of ground motions at the site.

Within this study are embedded several major subtasks that are required as inputs to various phases of the ground motion analyses. These include 1) geologic source characterization of the Teton fault, 2) analyses of seismicity in the region of the Teton fault and Jackson Lake Dam, 3) analyses of the crustal basin velocity structure and seismic response, 4) empirical site response analyses based on specific foundation conditions and recorded data at Jackson Lake Dam, and 5) development of ground motions from the Teton fault for Jackson Lake Dam considering the integrated results of the previous tasks. As a final step, these results are portrayed in a simplified probabilistic framework to facilitate their input to Reclamation risk assessments for Jackson Lake Dam. Analyses of data from the Jackson Lake Seismic Network (JLSN) and from site-response instrumentation operated at Jackson Lake Dam between 1996-2002 in conjunction with the JLSN are major inputs to all of these subtasks.

1.2.1 Teton Fault Source Characterization. This task includes the compilation of geologic data on the distribution and rate of paleoearthquakes on the Teton fault. Quaternary fault scarps and faulted Quaternary deposits define the length of surface rupture associated with past earthquakes on the Teton fault. These data also provide information on the size, age and frequency of faulting events, and on the geometry of individual fault planes associated with paleoearthquakes on the fault. For ground motion analyses, the objective is to describe the constraints imposed by the available data on the location (coordinate information), orientation (strike and dip), and slip characteristics (slip per event) of fault planes associated with potential earthquakes on the Teton fault. For probabilistic analyses, it is necessary to describe the extent, size, ages, and frequency of paleoearthquakes along the fault, or to describe the behavior of the fault in terms of a slip rate and various models of earthquake occurrence. For both ground motion and probabilistic analyses, it is necessary to consider potential alternative models of fault behavior and the uncertainties in descriptive data and fault models. The scope of the present investigation consists of a brief review and compilation of data from previous studies that have been conducted on the Teton fault. No new data collection or significant re-analyses of existing data have been conducted.

1.2.2 Seismicity Analyses. As part of this task, seismicity recorded by the JLSN between 1986-2002 were reanalyzed to provide refined regional (network-scale) velocity models, locations, magnitudes, focal mechanisms and recurrence information. The large and spatially diverse seismicity catalog from the JLSN provide a rich data set that were used to improve the regional velocity models used for preliminary locations of earthquakes within the JLSN. Improved earthquake locations allow enhanced discrimination of specific earthquakes that might be associated with the Teton fault and related structures and more reliable characterization of stress and slip regimes. Stress and slip information are primary inputs to describing the earthquake source and the velocity models are a primary input for evaluating seismic radiation from the source. Recurrence analyses are used in characterizing the probability of ground motions at the site.

1.2.3 Hanging Wall Crustal Velocity Structure.

Rupture directivity can be a significant issue for sites where fault planes have moderate- to shallow-dips and fault rupture extends beneath the site of interest. For scenarios in which the Teton fault dips less than about 50°, significant fault rupture on the northern and central sections of the Teton fault would include rupture at depth directly beneath or adjacent to the damsite. The impacts of 3D crustal velocity structure are also substantial, and to model these effects, data from a mini-array of three-component digital broadband stations operated in the vicinity of the dam in conjunction with the JLSN from October 1995 to May 2001 is used. Through waveform and traveltime modeling, the geometry and extent of the low-velocity basin surrounding the damsite area can be further resolved, and P- and S-wave velocities, and attenuation (Qp and Qs) characteristics defined to support the rock and soil ground motion simulations for the site.

1.2.4 Empirical Site Response.

Bedrock ground motions propagating from the Teton fault will be considerably modified by the near-surface soil column underlying much of Jackson Lake Dam. Recordings of strong ground shaking at the dam that could be used to directly estimate this effect do not exist. As a practical matter, since nearby large earthquakes occur infrequently, only the weak-motion recordings from smaller, more frequently occurring earthquakes are available. Ground motions from moderate-magnitude local earthquakes were recorded by three-component broadband velocity seismometers at six locations at Jackson Lake Dam. Recordings from the six sensors were compared to a reference location near the right abutment in order to estimate the weak-motion site response.

Computer codes for estimating the strong-motion site response are commonly based on one-dimensional models. These codes tend to underestimate the observed duration of shaking at Jackson Lake Dam. In order to partially account for the two and three-dimensional character of the observed weak-motion site response, yet employ available one-dimensional codes for estimating non-linear site response, a hybrid approach was used. This approach incorporates the longer durations observed from the weak-motion response to modify the input motions for use in one-dimensional computer codes.

1.2.5 Ground Motion Estimation for Jackson Lake Dam.

The influences of large-scale crustal velocity structure and source radiation on rock and soil ground motions at Jackson Lake Dam are the focus of this section. Ground motions are synthesized for the rock site station JLDW for a variety of magnitudes and source geometries to quantify peak ground motions scaling and variability associated with earthquake rupture scenarios postulated for earthquakes on the Teton fault. The uncertainties in fault dip are accounted for by considering multiple values of dip for each fault segment; thus as fault dip decreases, fault area and moment increase. A total of six fault segment and dip scenarios are considered when simulating ground motions. Rupture of the northern segment of the fault for dips of 35° and 45° involves fault rupture directly beneath the dam. It is necessary to determine how strongly rupture directivity may influence peak ground motions and ground motion variability at the dam for all of these near-source earthquake scenarios. Impacts of 3D crustal velocity structure are substantial and much of the modeling effort is devoted to accounting for the influences of 3D velocity heterogeneity on ground motion amplitudes and durations, and evaluating the influence of fault dip uncertainties on ground motion characteristics

1.3 Jackson Lake Dam

Jackson Lake Dam is located on the South Fork of the Snake River about 48 km (30 mi) north of Jackson, Wyoming. The dam and reservoir provide water storage for the Minidoka Project, an irrigation project along the Snake River in southeastern Idaho. The dam and reservoir were left as inholdings when the Grand Teton National Park was initially established in 1929.

Jackson Lake Dam was originally constructed by the Bureau of Reclamation in 1907, rebuilt in 1911 and enlarged in 1916. The resultant dam was a composite structure consisting of a short (south) embankment section on the right abutment adjacent to Signal Mountain, a short combined concrete spillway and outlet works section across the former channel of the Snake River, and a long embankment section that extended north across the Pilgram Creek alluvial fan. By the mid-1970's it was recognized that aspects of the original construction were potentially susceptible to earthquake-induced failure. Initial modifications to the concrete section were completed in 1977, but since much of the original embankment sections were constructed with hydraulic fill methods and minimal foundation treatments, more extensive investigations and analyses were required. Following these studies of potential earthquake hazards, foundation conditions, and alternatives, additional modifications were completed to the dam by 1989. These modifications included major changes to roadways that sit atop the south embankment and concrete section, widening of the south embankment, further modifications to the concrete sections of the dam, and complete reconstruction of the north embankment with extensive strengthening of the underlying foundation. Strengthening of the north embankment foundation was accomplished through dynamic compaction along the entire length of the dam and through construction of variably-sized SMW (concrete-soil mix walls) at the upstream and downstream toes of the embankment from the concrete section north to approximately station 29+00 (Stelma, 1996) (Figure 1-2).

The present dam has a total crest length of about 1500 m (4920 ft) at elevation 2066.7 m (6780.5 ft). The dam impounds a reservoir containing 7.7 x 10^8 m^3 (624,000 acre-ft) at the normal operating pool elevation of 2060.4 m (6760 ft).

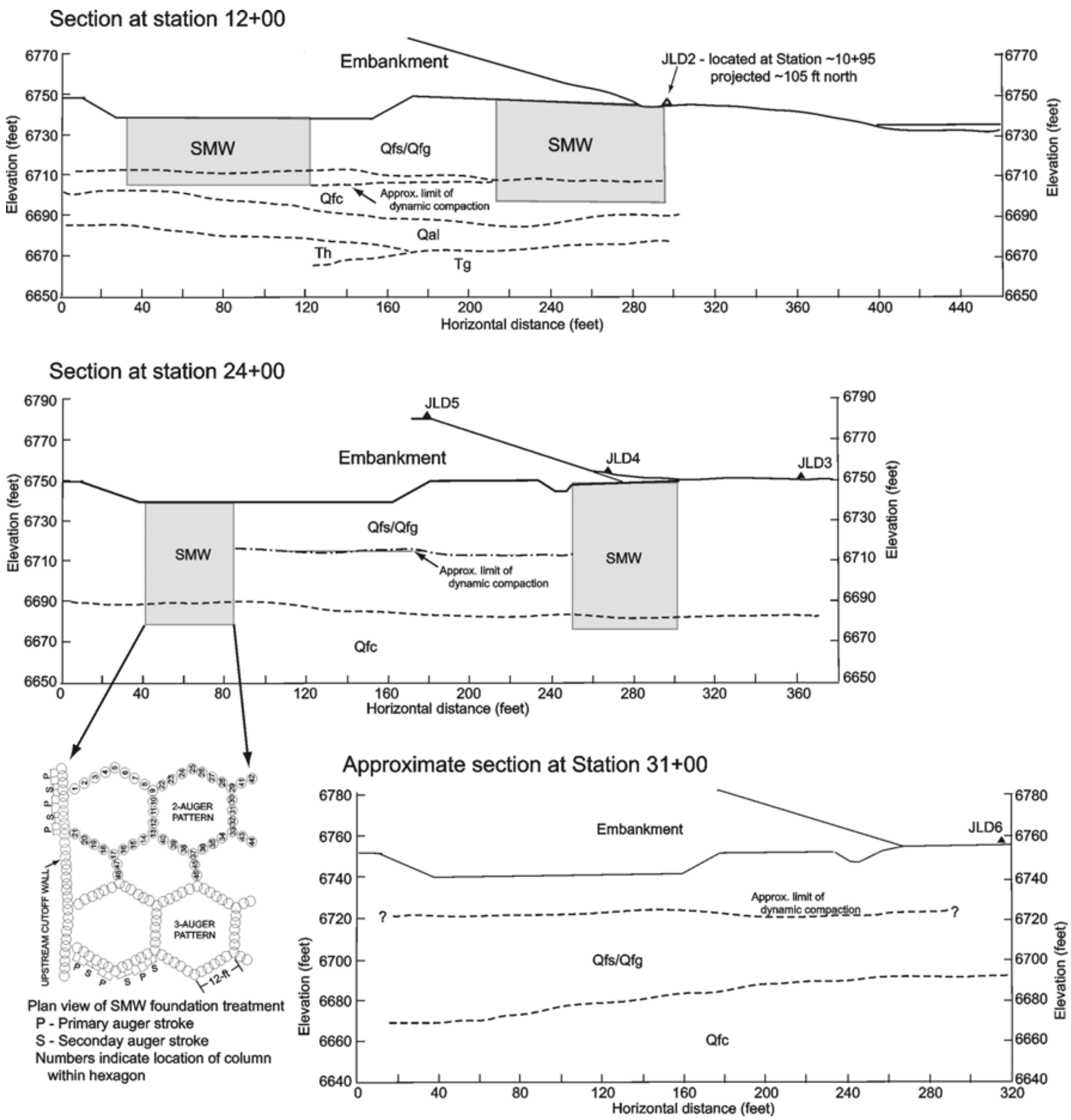

Figure 1-2: Schematic sections through Jackson Lake Dam at stations 12+00, 24+00, and 31+00. Extent of SMW treatment is shown by shaded boxes and in plan view sketch. Extent of dynamic compaction treatment zone is indicated by dot-dash line. Positions of seismographs sensors used to evaluate site response are indicated with triangles and labels. Sections and geologic data are modified from Stelma (1996). See text and Figure 1-3 for geologic legend and explanation.

1.3.1 Geologic Setting of the Dam. The right (south) abutment of Jackson Lake Dam is founded on the northern edge of Signal Mountain, a west-tilted block of early- to pre-Quaternary volcanic rocks and sediments capped by a thin veneer of young glacial deposits. Signal Mountain and Blacktail Butte (located further south in Jackson Hole) delineate the approximate western limit of pre-Quaternary rocks within Jackson Hole adjacent to the Teton fault (Figure 1-1 and Plate 4-1). West of these areas and extending nearly to the Teton fault, lies a thick sequence of Quaternary glacial deposits and alluvium; east of these areas are older Cenozoic alluvial deposits and weakly consolidated Mesozoic sedimentary rocks (Love et al., 1992). Quaternary glaciers flowing into Jackson Hole headed on the Yellowstone/Absaroka source area north and east of Jackson Lake Dam (e.g. Pierce and Good, 1992). Thick lobes of ice flowing through the damsite area excavated deep scour troughs that rapidly filled with alluvial and lacustrine deposits as the glaciers retreated (Pierce and Good, 1992; Smith et al., 1993). Jackson Lake Dam is located on one edge of a deep glacial scour trough that lies north of Signal Mountain. This trough probably extends several kilometers west of the dam beneath Jackson Lake, but probably bifurcates to the east and northeast in the damsite area. Near the present damsite, ice lobes flowing west, up the present Snake River, and west-southwest through the Emma Matilda Lake area joined. Thus, the northern extent of the scour trough is not well defined and likely extends well beyond the northern end of Jackson Lake Dam. As a result, the south embankment and concrete sections of Jackson Lake Dam are founded on variably compacted to over-compacted glacial deposits and Huckleberry Ridge Tuff while the north embankment section of the dam is constructed on a northward-thickening wedge of post-glacial alluvium and lacustrine units deposited on top of a compact glacial deposit (Figure 1-3; USBR, 1987). At the northern end of the dam, these relatively unconsolidated post-glacial deposits reach a thickness of about 180 m (600 ft). The presence of the glacial scour trough, and the large velocity contrast between the post-glacial alluvial fill and the underlying, older units are significant factors for estimation of ground motions at the site.

Material properties of the uppermost section of the post-glacial alluvial fill were derived from extensive drilling along the footprint of the dam that was done in conjunction with design and construction of the modification (Lockhart, 1986; Stelma, 1986; USBR, 1987). A limited number

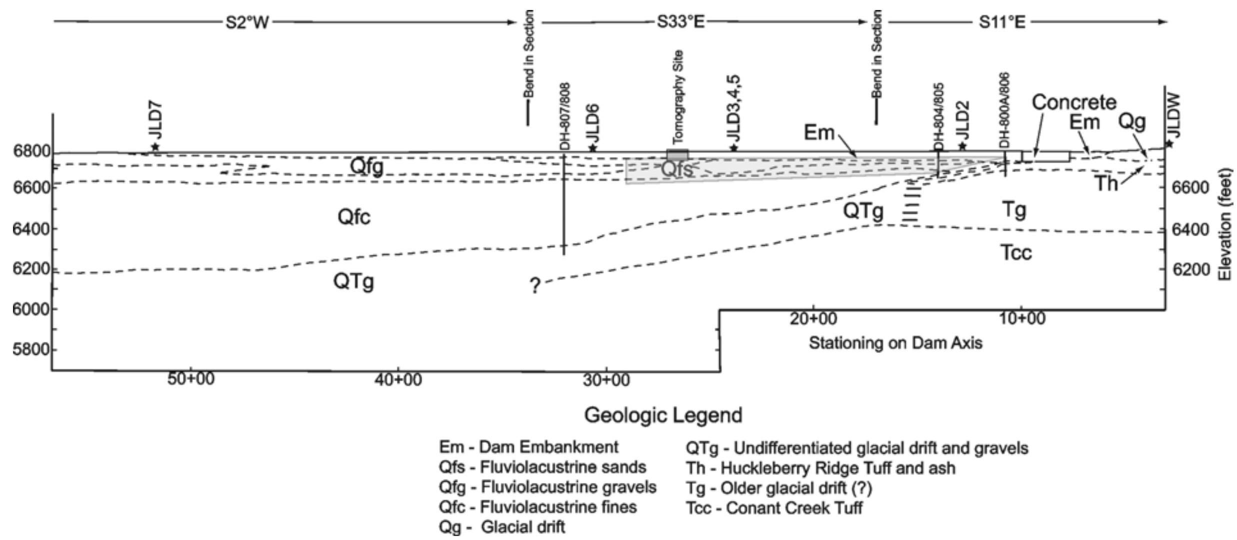

Figure 1-3: Generalized geologic cross section along the axis of Jackson Lake Dam. Foundation treatment consisting of SMW (shaded area) along the upstream and downstream toe of the embankment extended from the concrete section north to station 29+00 (see Figure 1-2). Dynamic compaction foundation treatment was completed beneath the embankment section north of the concrete section from about station 11+00 to about JLD7. Drillholes with geophysical logs (Sirles, 1986) are shown and labeled. Tomography site (Wright, 1990) is shown with grey box. Seismometer sites are shown with stars and labels. Geologic data compiled and modified from Gilbert et al. (1983), Lockhart (1986), USBR (1986), and Stelma (1996). View to east, looking downstream.

of drillholes penetrated the entire section. As part of these investigations, the alluvial fill beneath the northern embankment was described as three complexly interbedded subunits (USBR, 1987).

> "The subunit termed gravel (Qfg) of the fluviolacustrine sediments consits of predominantly coarse sand and gravel, but may include some oversize, as indicated by drilling conditions observed while advancing the boreholes. Deposits of the subunit are saturated, loose, unconsolidated, and range from nonstratified to poorly stratified. Wash cuttings returned from the Qfg consist of fragments of quartzite and other metamorphics and some volcanics.
>
> The subunit termed sand (Qfs) of the fluviolacustrine sediments consists of predominantly fine-grained sand but includes variable amounts of the medium and coarse sand fractions. The Qfs is saturated, loose, unconsolidated, and poorly stratified. Deposits of the Qfs subunit may contain a variable range of organic matter varying from less than 1 up to 5 percent.

The subunits termed fines (Qfc) of the fluviolacustrine sediments is composed of clay, silt, and very fine-grained sand. The Qfc is soft, unconsolidated, and ranges from thinly bedded to laminated, with minor and scattered sand and gravel lenses."

In contrast to the fluviolacustrine deposits that underlie Jackson Lake Dam, other deposits in the foundation (Figure 1-3) are much more consolidated and hard. The contrast in material properties is shown by a limited suite of geophysical investigations (Sirles, 1986; Wright, 1990) which provides geophysical properties that can be directly used in modeling of ground motions at the site and interpretation of site response data gathered from instruments at the dam. These data are discussed in more detail in Sections 5 and 6 in conjunction with site response and ground motion modeling.

1.3.2 Previous Seismic Hazard and Ground Motion Studies. No formal investigations of seismic hazards or ground motions are documented in association with the original dam construction in the early 1900's. In support of the modification studies of Jackson Lake Dam in the late 1970's and early 1980's, Reclamation conducted extensive seismic hazard analyses to develop earthquake loadings that were used in developing modification designs for the dam. These seismic hazard studies (Gilbert et al., 1983) included the first compilation and recognition of the extent of late Quaternary fault scarps along the Teton fault and established an MCE (Maximum Credible Earthquake) of M_L7.5 for the Teton fault as the most significant seismic source for Jackson Lake Dam. Gilbert et al. also identified other local and regional earthquake sources of potential significance, provided assessments for potential surface faulting at the site, coseismic subsidence and tilting of the damsite and reservoir basin which could lead to differential elevation changes and seiche waves in the reservoir, and seismically-induced landslides around the reservoir. Seismic loadings and ground motions for the Teton fault used in analyses of the proposed modifications were developed with input from a consultant board that provided review of the proposed modification designs and are documented in numerous technical memoradums (USBR, 1987). Details of the input motions varied slightly based on needs for individual analyses, but most were based on a time history record for the MCE that used a modified Pacoima-Taft record with a peak acceleration between 0.57-0.75 g and durations of 20-38 seconds as the input bedrock motions. Based on inputs from the consultant board, these motions were propagated through the alluvial fill beneath the embankment sections and resultant free-field motions at the toe of the embankment sections ranged between 0.25 - 0.36 g.

Based on recommendations contained in Gilbert et al. (1983) the Jackson Lake Seismic Network (JLSN) was established in 1986. Wood (1986) describes the initial configuration and operation of the network. Data from the JLSN used in analyses for this report are discussed in Section 3.

Recently, Wong et al. (2000) completed a preliminary probabilistic seismic hazard analyses for Jackson Lake Dam and other nearby Reclamation dams. Their analyses provided input bedrock motions which included the hazard contributions from both the Teton fault as well as numerous other nearby and regional seismic sources. For return periods of 10,000 and 50,000 years respectively, the estimated peak horizontal accelerations were 0.89 and 1.19 g, and the 1.0 sec spectral accelerations were 0.91 and 1.42 g. Review of the results in Wong et al. indicate that for all return periods greater than about 100-200 years, the Teton fault is the dominant contributor to input bedrock ground motions at the Jackson Lake Dam site.

1.4 Acknowledgements

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